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Psychophysical masking studies examined conditions in which the basic task was the detection of a target sound presented simultaneously with maskers whose component frequencies changed with each presentation. Experiments focused on the important determinants of performance when maskers are randomized. Specifice experiments fourn (1) that psychometric functions for individual maskers were extremely shallow relative to slopes under minimal uncertainty, (2) that the masking produced by combinations of broadband noise and multicomponent maskers was greater than that predicted from a linear sum of the effects of each masker alone (3) that the effects of masker uncertainty were greatly reduced or eliminated in forward masking (4) that the large individual differences observed were not reflected in measures of peripheral filter shape, and (5) that masking produced by uncertainty was extremely resistant to change as masker energy was progressively removed from the frequency region around the signal.

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Name	Position Title	% Effort
Neff, Donna L.	Principal Investigator	50%
Jesteadt, Walt	Co-Investigator	10%
Callaghan, Brian P.	Research Assistant	100%

I. Abstract:

Whereas most psychophysical masking studies are structured to minimize the influence of central processes, these experiments examined conditions in which central processes can have a marked influence upon performance. The basic task was the detection of a target sound presented simultaneously with maskers whose component frequencies changed with each presentation. The experiments completed in Year 1 focused on the important determinants of performance when maskers are randomized, and the relation between peripheral and central processes. Specific experiments with high masker uncertainty found 1) that psychometric functions for individual maskers were extremely shallow relative to slopes under minimal uncertainty, 2) that the masking produced by combinations of broadband noise and multicomponent maskers was greater than that predicted from a linear sum of the effects of each masker alone, 3) that the effects of masker uncertainty were greatly reduced or eliminated in forward masking, 4) that the large individual differences observed were not reflected in measures of peripheral filter shape, and 4) that masking produced by uncertainty was extremely resistant to change as masker energy was progressively removed from the frequency region around the signal.

II. Research Objectives and Statement of Progress:

A. Introduction. Many listeners have a great deal of difficulty detecting a highly familiar target sound in the presence of rather simple background sounds that change with each stimulus presentation. This difficulty cannot be explained in terms of traditional detection models that consider only energy falling within a single peripheral auditory filter centered at the signal frequency. The long-term goal of this project is to establish the factors that produce masking under conditions of high stimulus uncertainty, and to use this information to develop a more general model of signal detection. For Studies 1 and 3 described below, the majority of the data were collected before the start of AFOSR funding, however, either data collection for additional conditions or extensive data analysis occurred during Year 1 of the grant.

B. <u>Standard Stimuli</u>. Unless specified, the signal was a 200-ms, 1000-Hz sinusoid, and listeners are highly trained to detect this signal. The maskers were composed of multiple sinusoids, drawn from a 300-3000 Hz range that excluded the signal frequency and components within a 160-Hz critical band around the signal. Component amplitudes were equal, and total power was equated across conditions regardless of the number of masker components. The 200-ms maskers were presented simultaneously with the signal, both with 5-ms, cosine-squared, onset/offset ramps. The number of the components in the maskers was varied from 2 to 100 across conditions.

C. <u>Levels of Uncertainty</u>. To help demonstrate and quantify the contribution of more central processes, two levels of masker uncertainty were compared in each experiment. "Within-trial" variation, in which the frequency composition of the masker was changed with each stimulus presentation, was contrasted to "between-trials" variation, in which the same masker was used for the two intervals of a trial, but a different masker was drawn for each trial. When noted, conditions of "minimal uncertainty" refer to using the same masker throughout a block of trials. Any release from masking produced simply by reducing uncertainty cannot be attributed to peripheral energy-based processes.

D. <u>Summaries of Specific Experiments</u>.

1. <u>Measurement of psychometric functions</u>. This study addressed both the nature of the central processor and the adequacy of our measurement procedures. The majority of studies in this research project have used a "cued" two-alternative, forced-choice, adaptive procedure to estimate signal threshold. The cue was the signal presented alone in quiet before each trial. The standard deviations associated with these threshold estimates with multicomponent maskers tended to be higher than for sinusoidal or noise maskers (5-10 dB rather than 2-3 dB). This suggested that psychometric functions might be shallow for multicomponent maskers with few components, perhaps because the adaptive procedure was sampling from many different steep functions. Therefore, both adaptive thresholds and corresponding psychometric functions were obtained for 10-component maskers both for within- and between-trial masker variation. The psychometric functions for both levels of uncertainty were indeed shallow, typically spanning a range of 30-40 dB compared to the 10-dB range for broadband noise. Thresholds derived from the functions were in good agreement with thresholds measured adaptively. For between-trial masker

variation (within-trial not being possible), 50 of the original 200 masker waveforms were randomly selected and psychometric functions were examined for each using signal levels from 10-80 dB SPL. These psychometric functions were well fitted in d-prime by signal-level coordinates and also typically spanned a 30-40 dB range. Adaptive thresholds based on a pool of 50 maskers did not differ significantly from those based on 200, and were in agreement with the average of the predicted thresholds across the 50 maskers from the psychometric functions. Although individual maskers could differ in effectiveness by 10-15 dB, the majority produced similar masking. Overall, the adaptive procedure was judged to characterize performance adequately. For two of the original four subjects still available, psychometric functions were obtained for each of the 50 maskers under conditions of minimal uncertainty. Preliminary analyses suggest that the slopes of the majority of these maskers did become steeper as uncertainty was reduced, as expected, but the range of slopes was broader than anticipated. Final analyses of these data should be completed in the next few months.

2. Combined masking by masker uncertainty and stimulus energy. One way to get a better understanding of masking associated with uncertainty is to see how it combines with peripheral masking. Combining multicomponent maskers with broadband noise should produce one of three results: 1) no effect of the less effective masker, 2) a release from masking relative to that observed for the multicomponent maskers alone because the noise would reduce the perceptual dissimilarity of the stimuli from trial to trial, or 3) additional masking beyond that expected from the energy summation of the two maskers, as has been observed with numerous combinations of simultaneous maskers. In this experiment, the effect of combining masking produced by spectral uncertainty to that produced by stimulus energy was examined. Growth-of-masking functions for broadband noise and for multicomponent maskers with 2, 6, 10, 50, and 100 components were used to select levels for individual maskers that produced 10, 20, 30, or 40 dB of masking. Multicomponent and noise maskers were then presented in equated and unequated combinations. Data collection and analysis were more difficult than anticipated because of long-term training effects and large individual differences. In general, however, additional masking beyond a power summation was measured, which for equated conditions decreased from around 12 to 2 dB as the number of components in the multicomponent masker increased from 2 to 100. The data were well fitted by Lutfi's model for combined simultaneous maskers, with exponents that systematically approached 1.0 as the number of components increased to approximate broadband noise.

3. Forward masking produced by masker uncertainty. This study examined the forward masking produced by a broadband noise, a 1000-Hz sinusoid, and the multicomponent maskers of uncertain frequency content previously used in simultaneous masking. The 10-ms, 1000-Hz signal was presented 0 to 32 ms after the offset of a 200-ms masker presented at 60, 70, or 80 dB SPL. For comparison, a small set of simultaneous-masking data with a 200-ms signal was also collected. Consistent with previous studies of simultaneous masking, the function relating amount of masking to the number of masker components was nonmonotonic for simultaneous masking, with a broad maximum for maskers with 10 components. Considerably more masking was produced by these maskers than by a broadband noise of equal total power. In contrast, the function for forward masking increased monotonically but remained well below the masking produced by noise. The variability (standard errors) both across listeners and for each listener within a condition was much smaller in forward masking, which is the reverse of the usual observation of more stable performance in simultaneous masking. Between 10-15 dB less masking was produced by the forward maskers. Temporal cues appeared to account for at least part of this difference. When the signal in simultaneous masking was shortened to 10 ms, temporally centered in the masker, the amount of masking observed was reduced to that observed in forward masking. This strongly suggests that the simultaneous thresholds were elevated by factors other than masker energy. Presumably the shortened signal made it possible to compare masker alone to signal-plus-masker within the same stimulus interval, leading to better detection.

4. Restricting masker range, and interactions of masker bandwidth and component density. Previous experiments demonstrated that large amounts of masking were produced by maskers with less than 10 components drawn at random from a large (300-300 Hz) frequency range. This experiment examined whether restricting the frequency range of the components to the high (1080-3000 Hz) or low (300-920 Hz) side of the masker would affect the amount of masking, for maskers with 2, 4, 6, 10, 50, and 100 components. For maskers with 2 or 10 components, the effect of widening or narrowing the masker bandwidth (with corresponding changes in component density) was examined. In two approaches to the "notch widening" experiment, components were removed either in successive linear 100-Hz steps to plus/minus 700 Hz, or in two logarithmic steps to 1 octave. For the "band narrowing" conditions, the components were progressively limited to within 1 1/2, 1, 1/2, and 1/4 octave around the signal, still excluding critical-band components. For two of four listeners who showed sufficient masking under the standard conditions of high masker uncertainty with the full masker range, limiting components to the high or low frequency side of the signal, or widening the notch around

the signal did little to improve performance. Typically, maskers limited to the lower frequencies produced slightly more masking than maskers with the full range or those limited to higher frequencies. Decreasing the level of uncertainty reduced threshold for maskers limited to high-frequency components, but did not affect performance for maskers limited to low frequencies, that is, the higher frequencies appeared to dominate performance. Paradoxically, forcing the components into narrower bandwidths around the signal could reduce masking by about 5 dB. For the other two listeners who showed little effect of masker uncertainty, performance was consistent with expectations based on stimulus energy. These large individual differences under conditions of masker uncertainty were not well predicted by measures of auditory filter shape with notched-noise maskers, which were similar across listeners.

E. Individual differences and training effects.

The issue of individual differences and training is pertinent to all the experiments in this area. Over the last four years of work with multicomponent simultaneous maskers under conditions of masker uncertainty, we have tested 22 listeners. After the initial experiments that demonstrated the effect, both the stimuli and procedures have been modified somewhat to reduce peripheral masking effects. Specifically, component amplitudes were changed from random to equated, masker components within the critical band around the signal were eliminated, and, perhaps most significantly, a signal cue, as described earlier, was added before each trial. Whether as a result of these changes or of the particular subjects available, approximately half of our subjects now either initially show little effect of masker uncertainty or, more frequently, show large effects that decrease significantly with training. We have labeled these listeners "high-" versus "low-threshold" listeners. It may be that we forced many listeners into an analytical mode that they otherwise would not have adopted under conditions of masker uncertainty. Of even more interest is the fact that "high-threshold" listeners often did not obtain a release from masking produced by stimulus uncertainty even under rather extreme stimuli conditions (e.g., no masker energy below the signal, or 1000-Hz wide gaps in the masker spectra around the signal). For these listeners, it seemed that a strategy for processing the stimuli had been adopted that was extremely resistant to change.

III. Publications:

A. Published papers (reprints included):

Neff, D.L. and Callaghan, B.P. (1987). "Simultaneous masking by small numbers of sinusoids under conditions of uncertainty," in Auditory Processing of Complex Sounds, edited by W.A. Yost and C.S. Watson (Erlbaum: Hillsdale, New Jersey), 37-46.

Neff, D.L. and Callaghan, B.P. (1988). "Effective properties of multicomponent simultaneous maskers under conditions of uncertainty," J. Acoust. Soc. Am., 83, 1833-1838.

B. <u>Manuscripts in preparation</u>:

Neff D.L. "Forward masking by multicomponent maskers under conditions of uncertainty," to be submitted to J. Acoust. Soc. Am. in 1988.

Neff, D.L. and Callaghan, B.P. "Psychometric functions for multicomponent maskers under varying degrees of masker uncertainty," to be submitted to J. Acoust. Soc. Am. in 1988.

C. <u>Presentations with published abstracts</u>:

Neff, D.L., Jesteadt, W., and Callaghan, B.P. (1988). "Combined masking under conditions of high uncertainty," J. Acoust. Soc. Am. Suppl. 1, 83, S33.

Neff, D.L. and Callaghan, B.P. (1988). "Frequency effects for multicomponent maskers with high spectral uncertainty, " J. Acoust. Soc. Am. Suppl. 1, 84, accepted for publication.

D. <u>Other presentations</u>:

Neff, D.L. (1987). "Detection of familiar signals in arbitrary backgrounds," AFOSR Conference, December 1987, Chicago, IL.

Neff, D.L. (1988). "Detection of familiar target sounds in the presense of constantly changing background sounds." Colloquium Series, Psychology Department, University of Nebraska, September 1987, Lincoln, NE.

IV. Consultants.

Dr. David M. Green, from the University of Florida at Gainsville, spent two days in our laboratory in December 1987. Although funds were allocated in the grant for his visit, they were not needed, as Dr. Green simply extended his stay in Omaha after an Advisory Board Meeting for the Institute. Discussions with Dr. Green on theoretical issues related to psychometric functions and the relation of our research to his work in profile analysis were particularly useful. Given the availability of consultant funds, we also invited Dr. Robert Lutfi, from the Waisman Center in Madison, Wisconsin, to come for a two day visit in September 1988. Dr. Lutfi's recent work in the area of informational masking is directly relevant to our research program.

Effective properties of multicomponent simultaneous maskers under conditions of uncertainty[a)]

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When more than one sinusoid is used as a masker, more masking is observed than would be predicted by a simple combination of their individual effects. This masking is dramatically increased when the masker components vary in frequency and intensity with each presentation. These studies manipulated several masker parameters under conditions of high masker uncertainty, examining the effect of excluding critical-band components, fixing or randomizing component amplitudes and frequencies, and narrowing the frequency range of the components. The signal was always a 200-ms, 1000-Hz sinusoid, presented simultaneously with the 200-ms masker. Removing critical-band components reduced the amount of masking, but considerable masking remained that appears to be nonperipheral in origin. Fixing masker frequencies across the two intervals of a trial greatly reduced the masking observed, whereas fixing masker amplitudes had no effect. Reducing the frequency range from 5000 to 2700 Hz generally increased the masking observed, but appeared to depend on other masker parameters. Summaries across ten listeners show individual differences that are resistant to extensive training. It is difficult to account for most of the masking observed in terms of masker energy falling near the region of the signal.

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INTRODUCTION

This study is based on Neff and Green (1987), who examined the masking produced by simultaneous maskers composed of small numbers of sinusoidal components. Unlike a number of other studies using similar multicomponent maskers, Neff and Green varied the frequencies and amplitudes of the masker components with each presentation. Although the signal was a single sinusoid of fixed frequency and the listeners had extensive practice with that frequency, the masker uncertainty produced large amounts of masking. For example, as much as 55 dB of masking was measured in some conditions with ten-component maskers. Although masker uncertainty has been shown to elevate signal thresholds in both forward and simultaneous masking (e.g., Spiegel *et al.*, 1981; Watson *et al.*, 1976), these data were unusual in two respects. First, the magnitude of the effect was far larger than that observed in other studies of simultaneous masking, probably because earlier studies usually varied maskers across but not within trials. Second, very few masker components fell near the signal frequency, especially for maskers with ten or less components, because the component frequencies were drawn at random from such a wide range (5000 Hz). This second factor, combined with the fact that the signal frequency was always known to the listener and fixed over many consecutive blocks of trials, makes it difficult to account for this masking in terms of traditional models of frequency analysis that depend on energy falling within a critical band around the signal.

Given the considerable evidence that critical-band models, or related models based on auditory filter shape, can accurately summarize so much data for simultaneous masking, why did listeners have such difficulty with these particular conditions? In this article, we examine the effect of several masker parameters in more detail to determine which aspects of these complex maskers most affect performance. In particular, we examine the contribution of critical-band components, the relative contribution of uncertainty in component frequency versus component amplitude, and the effect of component frequency range.

The elimination of components within a rectangular critical band centered at the signal frequency provides a further test of the relative contribution of peripheral factors to the masking observed as the number of components in the masker is varied. More complex, and probably more accurate, representations of the auditory filter could have been used, but we choose the simplest approach for this initial experiment. Our expectation was that eliminating critical-band components would have little effect for maskers with only a few components, as few would fall within the band in the first place. Of course, as the number of masker components increased, more and more components would fall near or within the critical band. In this case, masking should be reduced if these components were removed.

With regard to the randomization of component amplitudes and frequencies, we expected that the effect of spectral uncertainty would be significant. In a limited set of data, Neff and Green (1987) observed a large decrease in masking

[a)] Portions of this research were presented at the 111th meeting of the Acoustical Society of America [J. Acoust. Soc. Am. Suppl. 1 79, S47 (1986)] and at a workshop sponsored by the AFOSR in Sarasota, 1986. See Neff and Callaghan [in *Auditory Processing of Complex Sounds*, edited by W. A. Yost and C. S. Watson (Erlbaum, Hillsdale, NJ, 1987), pp. 37–46] for published proceedings of the latter.

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when the same masker was used for the two intervals *within* a trial, even if a new masker were drawn for every trial. There might also be a contribution of amplitude uncertainty as well, however, either in isolation or in combination with frequency uncertainty. Because our intent in the original study (Neff and Green, 1987) was to sum components to produce broadband noise, each component's amplitude was drawn at random from a Rayleigh distribution. In related experiments on profile analysis in which listeners were asked to detect an increment to 1 component in an 11-component masker, Kidd *et al.* (1986) found that increasing the amplitude variation of the components could significantly degrade performance. More pragmatically, because most previous studies of masker uncertainty or profile analysis with multicomponent maskers used equal amplitude components, we wished to eliminate amplitude variation in our stimuli if it had little effect.

The comparison of different ranges for component frequencies was also motivated by differences across studies. The first two experiments reported in this article used a frequency range of 300–3000 Hz, to enable closer comparisons to Spiegel *et al.* (1981), whereas Neff and Green (1987) used 0–5000 Hz. Somewhat different patterns of results were observed for comparable conditions, so a final experiment with a new group of listeners directly compared the effect of the frequency range of the components. If uncertainty about masker frequency composition were the primary factor producing the masking, a wider frequency range for the randomization might produce more masking. Alternately, components from the outer bounds of the wider range would be even farther removed from the signal, both in terms of perceptual similarity and energy within a critical band around the signal, and might, therefore, produce less masking.

Although the majority of the data reported here are from one group of four listeners, we have comparable data for a subset of conditions on three additional listeners, as well as the three listeners in Neff and Green (1987). All of these listeners received more training than is typical in simultaneous masking tasks with simpler stimuli, and the results of extensive training are reported for one group. As discussed and documented by Watson and others (Kidd *et al.*, 1986; Leek and Watson, 1984; Watson, 1980; Watson and Foyle, 1985), the time course of learning more complex auditory tasks may be lengthy. Our primary goal was to establish that the large amounts of masking and individual differences observed in key conditions were not easily eliminated by additional training.

I. METHOD

A. Listeners

Data are presented for two groups of listeners, L1–L4 in experiments 1 and 2, and L5–L7 in experiment 3. The listeners, who were paid for their participation, were 17 to 23 years old, and had quiet thresholds ranging from − 5 to 12 dB HL relative to ANSI (1969) standards for audiometric frequencies from 250–8000 Hz. Each received at least 10 h of practice with noise and sinusoidal simultaneous maskers before beginning practice with the multicomponent maskers described below. Each group of listeners was tested 2 h daily over a period of several months, with frequent breaks during the testing sessions. The stimuli were delivered monaurally over TDH-39 earphones to the better ear of listeners seated in individual soundproof rooms.

B. Stimuli and procedures

The signal was a 200-ms, 1000-Hz sinusoid, presented without onset/offset ramps. Several parameters of the multicomponent maskers were varied across experiments and compared to what were considered standard conditions. In the standard conditions, the maskers were composed of 2–200 sinusoids whose frequencies were drawn at random from 300–3000 Hz at 5-Hz intervals (to maintain orthogonality given stimulus duration). The signal frequency could not be drawn as a masker component. The phase of each component was drawn at random from a rectangular distribution, and the amplitude of each component was drawn at random from a Rayleigh distribution. For comparison, an analog broadband noise masker was used with the same total power and the same frequency range as the masker components (i.e., bandpass-filtered from 300–3000 Hz). Like the signal, both multicomponent and broadband-noise maskers were 200 ms (between 0-voltage points on the envelope), presented without onset/offset ramps. The maskers were presented at 60-dB SPL total power; the rms values of the masker waveforms were adjusted to be the same regardless of the number of masker components. Changes to these standard masker parameters in comparison conditions are described with each experiment.

The signal, the multicomponent maskers, and a digital gating envelope for the analog broadband masker were computer generated, played through 16-bit digital-to-analog converters at a rate of 20 000 points/s, and low-pass filtered at 4000 Hz. A two-alternative, forced-choice (2AFC), adaptive procedure was used to measure signal threshold in quiet and in the presence of the multicomponent or broadband-noise maskers. The decision rule estimated the 70.7% correct point on the psychometric function (Levitt, 1971). An initial step size of 6 dB was reduced to 2 dB after the third reversal. Threshold was defined as the average of the reversal levels recorded during each 100-trial block, beginning with the third reversal. Amounts of masking (masked threshold minus quiet threshold) for the last nine 100-trial blocks for each condition were averaged for each listener.

Although the component frequencies varied, the number of components in the multicomponent maskers was constant for each block of trials. In a block of 100 trials, a different waveform was drawn at random (without replacement) from a file of 200 waveforms either for each stimulus presentation (i.e., each interval within a trial) or for each trial, as specified in the particular experiment.

To maximize the opportunity for learning for each condition, three consecutive 100-trial blocks with a specified number of components were completed before beginning the next condition in randomized order. In a further attempt to aid detection, the signal was presented in quiet before each block of trials. The listeners were instructed to concentrate on that frequency until they believed they had it firmly in memory, and then to initiate the block of trials.

II. RESULTS AND DISCUSSION

A. Experiment 1: Effect of critical-band components

In the original demonstration of large masking effects produced by small numbers of sinusoids of uncertain frequency (Neff and Green, 1987), masker components were allowed to fall as close as 5 Hz to the signal frequency. Although the majority of the masking observed seemed to be produced by central mechanisms linked to stimulus uncertainty, it is possible that peripheral mechanisms based on stimulus energy near the signal may also have contributed. It was argued that the contribution of "energetic" masking could not be large, however, as the probability of components falling near the signal was low in the conditions with the largest effects. In this experiment, we tested whether the elimination of masker components within a rectangular critical band around the signal frequency would affect performance. A fairly wide bandwidth was chosen based on Scharf (1970): 160 Hz wide, arithmetically centered around 1000 Hz. Although this does not eliminate energy falling within the auditory filter around 1000 Hz, it considerably reduces the potential contribution of peripheral factors.

The results, presented in Fig. 1, are averages and standard deviations across listeners L1–L4. Amount of masking is plotted for maskers with 2, 4, 6, 8, 10, 30, 50, 150, and 200 components. The dashed horizontal line indicates the corresponding average amount of masking produced by the broadband noise. As indicated by the error bars, the variability across listeners is substantial, particularly for maskers with ten or less components.

For maskers with 10 to 100 components, there is typically a 10-dB improvement in performance when critical-band (CB) components are excluded. This confirms expectations that removing critical-band components from maskers with larger numbers of components would improve performance simply because the probability of components

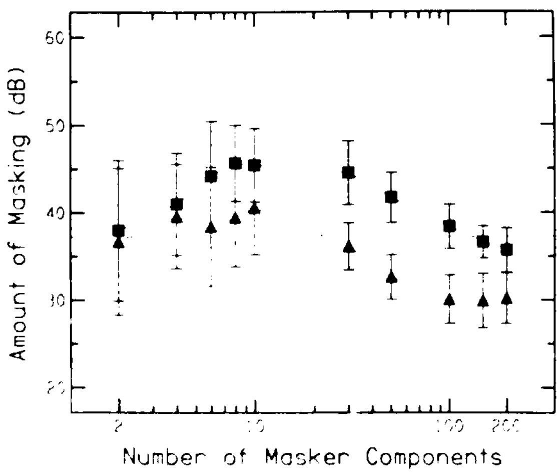

FIG. 1. Amount of masking produced by maskers with critical-band components included (squares) or excluded (triangles) as a function of the number of components in the maskers. The horizontal dashed line indicates the amount of masking produced by a broadband noise of equal total power. The data are means and standard deviations across four listeners (L1–L4).

falling within the band would be higher. For conditions with 100, 150, and 200 components, the largest numbers tested, the CB-excluded function appears to remain constant at about 30 dB of masking. This is probably a reasonable estimate of the masking that would be produced by a broadband-noise masker with a spectral notch the width of the critical band. If 30 dB is used as a reference in Fig. 1 rather than the dashed line, the increase in masking produced by uncertainty is even more pronounced. For large numbers of components, the CB-included maskers should eventually produce the same amount of masking as the broadband noise without a notch. This appears to occur with as few as 100 components, and results in a constant difference of about 7 dB between the CB-included and CB-excluded functions.

As was also predicted, there is no effect of removing critical-band components for maskers with only two and four components. For maskers with six, eight, or ten components, however, as much as 5 dB less masking is observed when the critical-band components are excluded. A repeated-measures analysis of variance (ANOVA) for these conditions, with subjects as the error term, indicated that this decrease, although small in absolute terms, was significant [$F(1,3) = 15.8$, $p < 0.05$]. Thus it appears that peripheral processes based on energy falling near the signal do contribute to the large amounts of masking observed. Even with critical-band components excluded, however, considerable masking remains that is unlikely to be based primarily on such peripheral processes. For example, 37 dB of masking is produced by only two components falling over a 2700-Hz range and over 40 dB is produced by ten components. This equals or exceeds the amount of masking produced by the broadband noise that has energy throughout the signal region. The predominant source of masking for these multicomponent maskers is probably more central processes related to stimulus uncertainty. Given the results of this experiment, critical-band components were excluded from the maskers in the remaining experiments, except for replications of earlier conditions, to reduce further the contribution of peripheral factors to the masking observed.

B. Experiment 2: Randomization of component amplitude and frequency

In the earlier study (Neff and Green, 1987) and in the conditions presented thus far, both component frequency and component amplitude were varied randomly across intervals within each trial. Although frequency uncertainty is certainly a major variable, variations in component amplitude might also contribute to the large amounts of masking observed, as outlined earlier. Further, if amplitude has no effect, it would be preferable to use equal amplitude components in future studies, both to simplify stimulus generation and to make comparisons to related experiments easier.

To assess the relative contribution of these factors, we compared the four combinations of randomizing or fixing amplitude and frequency *within a trial*: (1) randomized frequencies and fixed (equal) amplitudes; (2) randomized frequencies and randomized (Rayleigh) amplitudes; (3) fixed frequencies and randomized amplitudes; and (4) fixed frequencies and fixed (equal) amplitudes. Note that for the "fixed-frequency" conditions, different frequencies were still drawn for each new trial, so listeners sampled 100 waveforms within each block of trials. In previous studies of masker uncertainty, particularly that of Spiegel *et al.* (1981) which is most closely related to this study, variation across trials was the condition of maximum uncertainty.

The results are shown in Fig. 2. The data are averages across the same four listeners (L1–L4) as in the previous experiment. Error bars are omitted for clarity, but are similar to those for comparable conditions in Fig. 1. The upper functions with solid symbols denote conditions in which the component frequencies were drawn at random with each presentation, with either equal or random amplitudes. The lower functions with open symbols denote the corresponding conditions in which the component frequencies were fixed across the two intervals within a trial, with either equal or random amplitudes. Maskers with 2, 6, 10, 50, and 150 components were used, with components within the critical band around the signal excluded.

It is clear that there is little effect of manipulating either component frequency or amplitude for maskers with 50 or more components. For maskers with ten or less components, however, a repeated-measures ANOVA confirms that there is a significant effect of randomizing frequency [$F(1,3) = 20.1$, $p < 0.05$] with no significant effect of randomizing amplitude [$F(1,3) = 0.01$, $p > 0.05$]. For example, frequency randomization raised the amount of masking produced by two-component maskers by more than 15 dB relative to the fixed-frequency condition. Thus at least this much masking must be attributed to frequency uncertainty. Even for the fixed-frequency/equal-amplitude conditions, however, more masking is produced than would be predicted by classic critical-band or auditory-filter models. For example, over 35 dB of masking is produced by six-component maskers, although very few masker components would fall near the signal frequency (and none within the critical band around the signal).

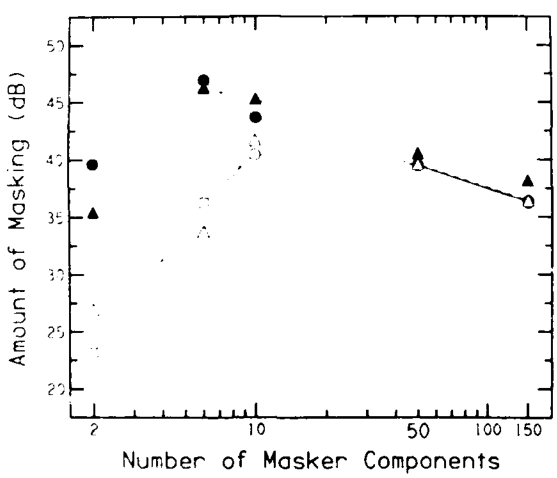

FIG. 2. Amount of masking produced by randomizing (filled symbols) or fixing (open symbols) the frequencies of the masker components across the two intervals of a trial for maskers with equal (circles) or random (triangles) amplitudes as a function of the number of components in the maskers. The data are means across the same four listeners as in Fig. 1.

Presumably, reducing the level of stimulus uncertainty another step by the use of a single masker sample across a block of trials, or across many consecutive blocks of trials, should further reduce the amount of masking observed. After extensive practice with each sample to remove the effect of stimulus uncertainty, we would expect little masking to remain, as these are relatively poor stimuli for energetic masking. Such conditions were not pursued, except for exploratory work, due to lack of time. Our initial inquiry suggested a lengthy undertaking, as the results appeared to depend on the particular masker sample chosen and the pool of potential samples was large. Less masking was observed in all conditions. Certainly, such conditions of "minimal uncertainty" (Watson *et al.*, 1976) need to be examined in more detail, in order to assess the relative contribution of peripheral and central effects.

C. Experiment 3: Bandwidth of randomization

This study examined whether changes in the range of frequencies from which masker components could be drawn, i.e., masker bandwidth, could contribute to the amount of masking observed under conditions of high frequency uncertainty. Masker bandwidth was the third major parameter, in addition to the presence or absence of critical-band components and amplitude randomization, that was changed in studies that followed the original Neff and Green study. Each of these parameters was of interest as possibly contributing to the somewhat different pattern of results observed in the original versus the later studies. For example, as summarized by the averages across listeners, Neff and Green observed much less masking for two-component maskers and much more masking for ten-component maskers than was observed in experiments 1 and 2. Thus the present study compared variation in masker bandwidth for two sets of stimuli, those used in Neff and Green and those used in most of our later studies, for a subset of conditions that showed the largest masking effects.

Three new listeners (L5–L7) were tested with multicomponent maskers with 2, 10, and 50 components. Except for the specific masker parameters to be described, all other aspects of the stimuli, and the procedures used to measure threshold, were identical to those outlined for experiments 1 and 2. Only conditions in which different masker samples were drawn for each presentation were tested (i.e., as in Neff and Green, experiment 1 above, and the random frequency conditions of experiment 2 above). One set of multicomponent maskers (set 1), replicating Neff and Green, had critical-band components included, random component amplitudes, and no onset/offset ramps. The other set of maskers (set 2), corresponding to later experiments, had no critical-band components, equal component amplitudes, and 5-ms onset/offset ramps. For set 2, the signal also had 5-ms ramps. For each of these sets of maskers, component frequencies were drawn at random from either a 0- to 5000-Hz range or a 300- to 3000-Hz range for the bandwidth comparison.

The results are shown in Fig. 3. The left panel presents results for maskers in set 1 (critical-band included, random amplitudes, no ramps); the right panel presents results for maskers in set 2 (critical-band excluded, equal amplitudes,

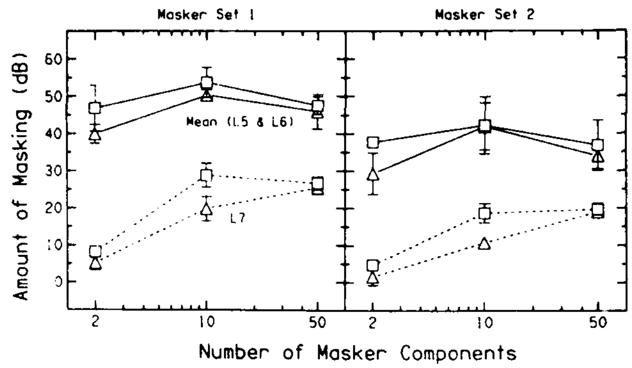

FIG. 3. Amount of masking as a function of the number of components for two sets of maskers (left and right panels). See text for stimulus details. Within each panel, data for 300- to 3000-Hz (squares) and 0- to 5000-Hz (triangles) ranges for component frequencies are compared for the mean across two listeners (upper solid lines) and for a third listener (lower dashed lines). The error bars are standard deviations across listeners or replications for the upper and lower sets of functions, respectively.

5-ms ramps). Within each panel, the two frequency ranges are compared for the average of two listeners who were similar (L5 and L6; upper functions with solid lines) and for a third listener who had much lower amounts of masking (L7; lower functions with dashed lines). The error bars thus reflect variation across listeners or variation across replications for the upper and lower sets of functions, respectively. Listener 7 shows the same pattern as the other listeners, but less masking than we have observed in this or previous studies, particularly for the ten-component condition. The importance of this difference is hard to assess, however, in that the quiet threshold for the signal for L7 was much higher than the thresholds for the other two listeners in this group (e.g., 18.0 dB vs 0.8 and 2.3 dB for signals without ramps). If plotted in terms of masked thresholds, performance for L7 would be more similar to the other listeners.

A repeated-measures ANOVA, with listeners as the error term, confirms the rather small but significant effect of changes in bandwidth seen in Fig. 3. Less masking is observed when the masker components are drawn from the wider (0- to 5000-Hz) frequency range [$F(1,2) = 46.35$, $p < 0.05$]. Averaged across listeners, this decrease ranges from 1.5–6.4 dB. Presumably, masking is reduced for the wider frequency range because of the greater probability of wider spacing between masker components and the signal frequency. This would particularly affect components on the high-frequency side of the signal, because the increase in bandwidth is skewed in that direction.

There is also a significant difference in the amount of masking produced by the two sets of stimuli (left versus right panels), with less masking produced by maskers in set 2 [$F(1,2) = 22.36, p < 0.05$]. This difference, which ranged from 6-[illegible] dB across conditions, is of the magnitude expected from experiment 1 on the effect of removing critical-band components. Although the addition of ramps or equal amplitudes might possibly also contribute to the decrease, the results of experiment 3 would predict amplitude effects of 1 or 2 dB at most. Overall, the magnitude of the reduction of masking for each stimulus set as a function of masker bandwidth was not large enough to dictate choices for future studies. As discussed in the next section, changes in the masker parameters examined also do not account for the differences observed across studies in the pattern of masking produced by maskers with varying numbers of components.

D. Individual differences and training

As indicated by the error bars in Fig. 1, the amounts of masking measured for individual listeners for a condition with small numbers of masker components can differ by 15 dB or more. These differences are very resistant to training, and, with the exception of L7 in experiment 3, cannot be attributed to variation in quiet thresholds. Training effects are best illustrated by listeners L1–L4 in the first experiment. For maskers with critical-band components included in which both component frequency and amplitude were varied, we ran 1800 trials for each condition, in blocks of 100 trials. Figures 4 and 5 show examples of learning curves for the four listeners for maskers with two and ten components, respectively. These conditions exhibited the largest learning effects, and then only for one listener, L1 in the upper left panels. For the other three listeners, sheer repetitive practice was not effective in improving performance in any condition. When learning occurred for L1, performance stabilized after 500–600 trials. Listener 2 (upper right), who was the only musician in the group, typically began with somewhat better performance, but did not improve with practice, as illustrated in Fig. 5. At least anecdotally, this agrees with the general summary that musicians may be "pretrained," but otherwise may differ little from highly trained listeners in specific auditory skills (Spiegel and Watson, 1984). To exclude any effects of learning, the data presented in experiments 1–3 were based on the last nine 100-trial blocks.

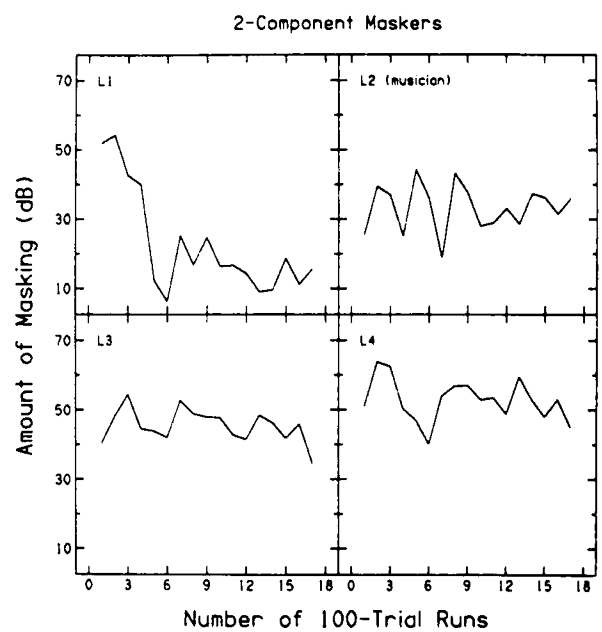

FIG. 4. Learning curves for maskers with two components for individual listeners, L1–L4. Amount of masking is plotted as a function of the number of 100-trial blocks completed, for a total of 1800 trials.

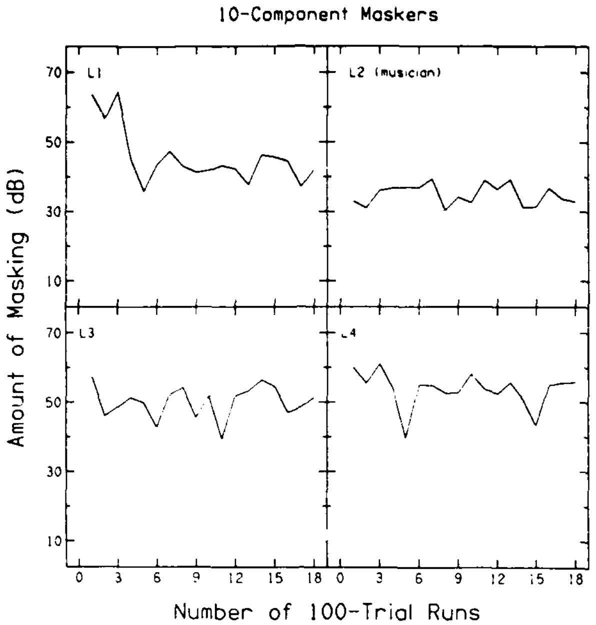

FIG. 5. Same as Fig. 4, except for maskers with ten components.

Despite the individual differences in performance illustrated here for L1–L4, the listeners all showed the same general pattern summarized by the average data in Fig. 1: large amounts of masking even for two-component maskers, which gradually increased to a broad maximum for ten-component maskers, followed by a decrease in masking as the number of components increased to 200. This pattern held whether critical-band components were included or excluded. The average data for three different listeners reported in Neff and Green (1987) showed a similar pattern, except that much less masking was observed for the two-component condition, and the amount of masking increased rapidly to a higher maximum of 55 dB as the number of masker components increased to ten. The small effect of changes in component frequency range investigated in experiment 3, as well as the lower thresholds for L7, suggest that these differences across groups stem from individual differences in abilities in auditory processing. These differences are also evident in the learning curves for experiment 1. Such differences are not unexpected for tasks that involve more central processes, as appears to be the case for this masking task.

III. SUMMARY AND CONCLUSIONS

Large amounts of simultaneous masking can be observed for a few sinusoidal masker components scattered over a wide frequency range under conditions of high masker uncertainty. Three experiments using a total of seven highly trained listeners examined important properties of the maskers. In experiment 1, it was determined that the occurrence of critical-band components can contribute to the masking observed. Even when critical-band components are removed, however, considerable masking remains which is difficult to attribute primarily to peripheral mechanisms. In experiment 2, it was determined that the frequency uncertainty of individual masker components was predominant in producing the effect, with no significant effect of amplitude uncertainty. In experiment 3, the amount of masking was decreased significantly, although the effect was 6.4 dB or less, when the frequency range of masker components was increased from 2700 to 5000 Hz. Individual differences exist that are not altered by extensive training with the 2AFC adaptive procedure. Despite these differences, the same general pattern held for nine of the ten listeners: large amounts of masking for maskers with ten or less components, followed by a gradual improvement in performance as the number of components increased. One listener showed much less masking overall than previously observed, although this was due, in part, to much higher thresholds in quiet. Both the lower thresholds observed for some listeners in some conditions and the release from masking when the same masker is used for both intervals within a trial indicate a large contribution of central processes to performance for the majority of listeners.

These results are intriguing in that listeners cannot use the single-filter approach postulated by classic models of signal detection, even though there is little or no masker energy in the signal region. Instead, dynamic properties of the maskers appear to interfere with such detection, although listeners are instructed to ignore the interfering stimuli and focus on the signal. The problem of quantifying the relative contribution of apparent peripheral versus more central or attentional mechanisms that limit performance remains.

ACKNOWLEDGMENTS

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Auditory Processing of Complex Sounds

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LEA

Simultaneous masking by small numbers of sinusoids unde conditions of uncertainty

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Threshold for a 1000-Hz sinusoidal signal was measured in the presence of simultaneous maskers compos of 2 to 200 sinusoidal components. Masker frequencies were drawn at random for each presentation from a range of 300-3000 Hz, excluding the signal frequency. To mim the properties of components drawn from noise, the ampl tude and phase of each component was drawn at random from Rayleigh or rectangular distributions, respectivel As in an earlier study, large amounts of masking were observed for maskers with very few components spread across a wide frequency range. In the first experiment eliminating masker components from a 160-Hz wide critic band around the signal reduced the amount of masking, b considerable masking remained even for maskers with 10 fewer components. In the second experiment, component frequencies, amplitudes, or both, were either fixed or randomized across the two listening intervals of a forced-choice trial; new frequencies were always presen ed on each successive trial. Amplitude randomization h no effect regardless of the number of components in the masker. Frequency randomization, however, produced lar amounts of masking for maskers with 10 or fewer compo- nents. These effects typically show little change with extensive practice, and appear to be produced primarily by nonperipheral processes.

INTRODUCTION

Masking is defined operationally as the reduction i the detectability of one sound, the signal, associated with the presentation of another sound, the masker. Masking experiments remain one of the primary tools for assessing the frequency selectivity of the human audito system (e.g., see Patterson and Green, 1978 and Scharf, 1970 for reviews). Out of these many studies has emerg a generally accepted view of frequency analysis in whic the peripheral auditory system is modeled as a bank of overlapping bandpass filters and the listener is assume to monitor a filter centered on or near the signal frequency where the ratio of signal energy to noise energy is optimum. Information outside this "critical band" is presumed to neither help nor hinder detection. Studies of psychophysical tuning curves, masking patterns, and auditory filter shape, to name a few, reflect this single-filter perspective.

In recent years, however, there has been considerabl interest in the ability of the auditory system to make use of information in regions far removed from the signa frequency to aid detection. A number of studies have provided evidence that listeners can indeed use information from filters distant from the signal frequency. A primary example is the work of Green and colleagues on profile analysis (e.g., Green, 1983; Spiegel et al., 1981). Green has shown that threshold for an increment to a single component of a multicomponent complex can be improved by as much as 20 dB if additional tones are added around the tone being incremented. Listeners appear to use these additional components, even when far outside the critical band, to build stimulus "profiles" in long-term memory and use these profiles to improve signal detection. Similarly, several studies of simultaneous masking report evidence of multichannel processe that aid signal detection (e.g., Buus, 1985; Hall et al. 1984). Hall and colleagues have shown that correlating the temporal envelopes of two stimuli in frequency regions far outside the critical band around the signal will reduce the influence of the maskers, an effect they call "comodulation masking release." Again, in all thes experiments, it is advantageous for the listener to make use of information in distant frequency regions. Perhap it is no great surprise that a sophisticated detection system can do that when required. The present experiments, however, focus on situations in which the listeners could greatly improve their performance by ignoring any information falling outside the signal region and focusing on the output of a single peripheral filter. Apparently, they are unable to behave as traditional models would predict, even if it is to their advantage to do so.

In the initial experiments (Neff and Green, 1986), our intent was to determine the minimum number of sinusoids necessary to produce the same amount of simultaneous masking as broadband noise. In the process, we discovered that small numbers of sinusoids could produce very large amounts of masking if the frequencies of the sinusoids were changed with each presentation. For example, as the number of sinusoids in the maskers was increased from 2 to 10, the average amount of masking increased from about 10 to 55 dB. The experiments reported here replicate the basic results of the original study, despite some modifications in the stimuli. (If changed, the original values are given in parentheses in the next section). The goals were to assess the effect of removing masker components from the critical band around the signal frequency, and to compare the effect of randomizing only frequency, only amplitude, or both on the amount of masking produced by the multicomponent maskers.

METHOD

Subjects. Four normal-hearing listeners were tested who received at least 10 hours of practice before data collection began. The stimuli were presented monaurally to the ear with the lower quiet threshold through TDH-39 headphones.

Stimuli. These were simultaneous masking experiments in which the threshold for a 1000-Hz signal was measured in the presence of multicomponent maskers. Note that the signal frequency was never changed and was presented in quiet before each block of trials. Both signal and masker were 200 ms, presented together without ramps. There were two kinds of maskers. One, which served primarily as a reference, was an analog broadband noise, bandpass filtered from 300-3000 Hz (or lowpass-filtered at 5000 Hz), and presented at 60 dB SPL total power. The rest of the maskers were multicomponent complexes in which the number of sinusoidal components was varied from 2 to 200 (or 100) across conditions. With the exception of the broadband noise, the stimuli were computer generated. For the multicomponent maskers, the component frequencies were drawn at random from the same frequency range as the broadband noise. The minimum frequency spacing between components was 5 Hz so that the components would be orthogonal. The signal frequency could not be drawn as a masker component. Because the original stimuli were intended to sum to make noise, the phase and amplitude of each component were randomly drawn from rectangular and Rayleigh distributions, respectively. The maskers had equal rms values of 60 dB SPL (or an expected value of 60 dB SPL with variation around that value).

Procedure. A two-alternative, forced-choice (2AFC), adaptive procedure was used to determine threshold for the signal in quiet and in the presence of a masker, with a decision rule that estimated the 70.7% correct point on the psychometric function (Levitt, 1971). An initial step size of 4 dB was reduced to 2 dB on the fourth reversal. Threshold was defined as the average of the reversal levels recorded during each 100-trial block beginning with the fourth reversal. For each condition, the number of components in the masker was specified and 200 masker waveforms (or 50) with that number of components were generated. In a block of 100 trials, a different masker was drawn at random from this large set for each interval of each trial. At least eight threshold estimates were obtained for each listener and condition. Except for Figure 4, the results presented are averages and standard errors across listeners.

COMPARISON ACROSS GROUPS

Figure 1 compares the average performance of the three listeners in the original experiment and the four listeners in the experiments to be described in the rest of the paper. In this figure (and also Figs. 2 and 3), the amount of masking of the 1000-Hz signal (i.e., masked threshold minus quiet threshold) is plotted as a function of the number of tones in the masker. Error bars are omitted for clarity. The light dashed line shows the

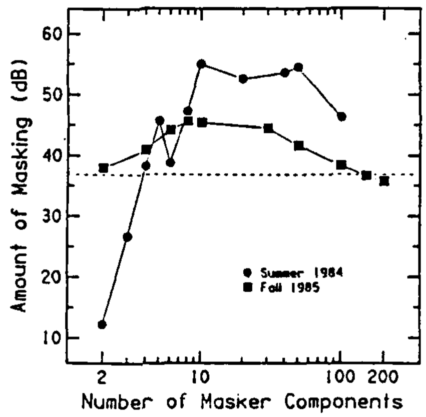

Figure 1. Amount of masking as a function of the number of components in the masker for two groups of listeners. See text for further details.

amount of masking produced by the broadband noise, which happened to be about 37 dB for both groups.

For the 1984 group, the function increased rapidly as the number of components was increased to 10, followed by a plateau or slight decline for maskers with more components. Maskers with 10 components produced up to 55 dB of masking. The masking produced by 100-component maskers was still greater than that produced by the broadband noise. For the 1985 group, the function is flatter. These listeners have much more difficulty with 2-component maskers, which produce almost 40 dB of masking, but about 10 dB less masking is observed for maskers with more than 10 components. The amount of masking equals that produced by broadband noise for maskers with 150 or 200 components. The differences across groups may be due to the use of a narrower frequency range with the later group (2700 vs. 5000 Hz) or perhaps simply to differences across listeners. The frequency range was changed because we were no longer using signals at low and high frequencies, as in the earlier experiments, and because our stimuli would then be similar to those used in related profile analysis experiments (e.g., Spiegel et al., 1981). However, the basic results are the same: large amounts of masking (up to 45 dB) can be measured with very few masker components scattered over a wide frequency range.

The randomization of spectra within a trial appears to be the major factor degrading performance. In the original group, we found that performance improved by as much as 25 dB when the same masker was presented within a trial, but different maskers were presented across trials. This is consistent with a form of profile analysis in which listeners apparently compare spectra across intervals to detect the signal.

CRITICAL BAND COMPONENTS INCLUDED OR EXCLUDED

This experiment tested whether eliminating masker components within a critical band around the signal would affect performance. For maskers with small numbers of components, the absence of critical-band components was not expected to have much effect on threshold, because so few components would fall within that band in the first place. For maskers with large numbers of components, more of an effect would be expected because more components would fall within the critical band. Given the different estimates of the critical band across studies

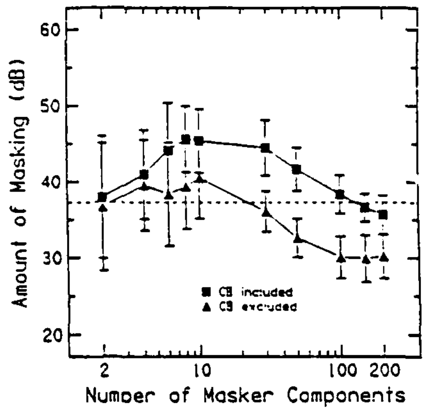

Figure 2. Amount of masking as a function of the number of components in the masker, for maskers with critical-band components included or excluded. See text for further details.

and procedures, a fairly wide bandwidth was chosen arbitrarily: 160-Hz wide arithmetically centered around 1000 Hz.

In Figure 2, the upper function is for maskers with critical-band components included; the lower function is for critical-band components excluded. The dashed horizontal line is the masking produced by the broadband noise, as in Fig. 1. The variability across listeners is substantial, particularly for maskers with 10 or less components. For maskers with more than 10 components, there is clearly less masking when critical-band components are excluded, as expected. For 2- and 4-component maskers, there is essentially no difference in the amounts of masking. For maskers with 6, 8, or 10 components, however, significantly less masking is observed when critical-band components are excluded ($p < .05$), although the effect is quite small (about 5 dB). Even without critical-band components, significant amounts of masking are produced (e.g., over 40 dB for maskers with 10 components; 37 dB for maskers with 2 components). Thus, it seems unlikely that this masking can be attributed primarily to peripheral processes based on energy near the signal frequency.

RANDOMIZATION OF AMPLITUDE AND FREQUENCY

In the data presented thus far, both component frequency and component amplitude were varied randomly across intervals within a trial. Certainly, spectral uncertainty is a major variable, but variations in component amplitude might also contribute to the large amounts of masking. Kidd et al. (1986) have shown that profile analysis can be degraded significantly by randomizing the amplitudes of the individual components that form a profile. Therefore, we compared four conditions of randomization within a trial: 1) randomized frequencies and fixed (equal) amplitudes; 2) randomized frequencies and randomized amplitudes; 3) fixed frequencies and fixed (equal) amplitudes; and 4) fixed frequencies and randomized amplitudes. For fixed-frequency conditions, different frequencies were still drawn for each new trial. The results are shown in Figure 3.

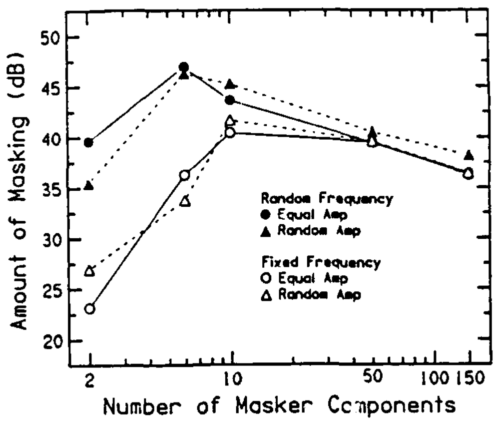

Figure 3. Amount of masking as a function of the number of components in the masker, for combinations of random or fixed component amplitudes and frequencies across the two intervals of a 2AFC trial.

For maskers with 50 or 150 components, there is no effect of manipulating either component frequency or amplitude. However, for maskers with 10 or less components, there is a highly significant effect ($p < .001$) of randomizing frequency with no significant effect of amplitude ($p > .05$). For 2-component maskers, for example, randomizing frequency raised the amount of masking by more than 15 dB relative to the fixed-frequency condition. Even for the fixed frequency/equal amplitude conditions, however, more masking is produced than would be predicted by classic critical-band models. For example, 6-component maskers produced up to 35 dB of masking, with very few components falling anywhere near the signa frequency. Again, nonperipheral processes envoked by stimulus uncertainty appear to limit performance.

INDIVIDUAL DIFFERENCES AND TRAINING

The effects observed for maskers with small numbers of components exhibit large individual differences that are very resistant to training. For conditions with critical-band components included in which both componen frequency and amplitude were varied, 1800 trials were presented in blocks of 100 trials. Figure 4 shows learning curves for two-component maskers. This condition had the largest training effect, although only one listener (L1-upper left) showed evidence of learning through sheer repetitive practice in this or any other condition. When learning occurred, performance stabilized after 500-600 trials. L2, who was the only musician in the group, typically began with better performance than anyone else, but he did not improve with time.

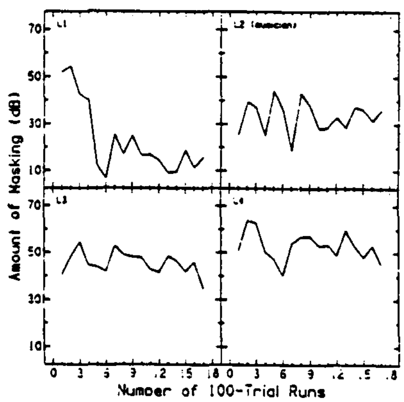

Figure 4. Learning curves for the four listeners for a masker with two components.

The observation of large amounts of masking that are very resistant to training, and the presence of substantial differences in performance both within listeners across repeated conditions and across listeners, is not unexpected for tasks with complex sti..uli (Watson, 1980). Large individual differences and learning over a long time course have been shown both for sequential ten-tone patterns, particularly under conditions of high stimulus uncertainty (e.g., Watson et al., 1976), and for profile analysis (Kidd et al., 1986). The general problem of why randomizing masker spectra within a trial produces so much masking remains unsolved.

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